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The Effect of Gasoline Reformulation and Sulfur Reduction on Exhaust Emissions from post-1983 but pre-1990 Vehicles

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Abstract

Ten post-1981 and pre-1990 vehicles were tested to determine if the effect of gasoline reformulation would be different than predicted by the EPA complex model. All vehicles passed the IM-240 screening before fuel testing. A nonoxygenated baseline and four oxygenated test fuels with varying levels of sulfur and RVP were tested for exhaust emissions. The emission response of the fuel changes with these vehicles was similar to that predicted by the complex model. However, the NOx emissions of the vehicles in this study were less sensitive to sulfur level than complex model predicts. Also, the oxygenated reformulated gasolines regardless of sulfur level produced greater reductions in NMHC emissions than predicted by the complex model.

Introduction

The purpose of this study was to investigate the effect of reformulated gasoline and especially sulfur content on pre-1990 model year vehicles. Reformulated gasoline's effect on emissions has been widely studied on 1990 technology vehicles to satisfy the requirements of the 1990 Clean Air Act Amendments (EPA, 1994). However, there will be older vehicles using reformulated gasoline when it is introduced beginning in 1995 with stricter standards implemented in the year 2000.

Under current regulations, in the year 2000 and beyond, reformulated gasoline will be required to reduce NOx emissions from 1990 vehicles. The reduction will be based on the EPA complex model which correlates emissions to fuel parameters. Sulfur content reduction is the most likely method to reduce NOx emissions. Sulfur poisons the catalyst which reduces the control efficiency.

While some studies (API, 1991; API, 1994; Schoonveld and Marshall (1991); Gething (1991); Jessup, et al. (1992)) have investigated pre- and post-1990 model year vehicles and others (AQIRP, 1991a) have investigated the fuel effects on pre-1990 vehicles exclusively, the primary interest in these studies was the effects of volatility, oxygen content, aromatic content, and the distillation properties of gasoline. A significant gap in the design of these studies is the effect of sulfur on emissions. In studies of newer vehicles (AQIRP, (1991b); AQIRP, (1992)), sulfur was shown to have a dramatic effect on emissions. The effect of sulfur level was determined to affect the performance of the catalyst. This study was designed to determine if sulfur reductions produced the same

Table 2 Vehicle Descriptions

Year	Model	Engine Family	Fuel System
1986	Mazda\B2000	GTK2.0T2HFL8	Carb.
1986	Chevrolet\Nova	GNT1.6V2HFF1	Carb.
1984	Honda\Accord	EHN1.8V3FEF0	Carb.
1983	Honda\Accord	Not Available	Carb.
1985	Chevrolet\Celebrity	FG2.5V5TPG7	TBI
1984	Pontiac\6000	EZG2.5V5TPG7	TBI
1986	Chevrolet\Cavalier	GIG2.0V5XAG2	TBI
1985	Mercury\Marquis	FFM3.8V5HHF8	TBI
1986	Ford\Tempo	GFM2.5V5HCF6	TBI
1985	Mercury\Cougar	FFM3.8V5HHF8	TBI

Table 1 Test Baseline and Test Fuels

Fuel\Parameter	CAAB[1]	Baseline[2]	Fuel 1	Fuel 2	Fuel 3	Fuel 4
RVP (psi)	8.7	8.7	8.2	8.2	8.2	6.9
Oxygen (wt. %)	0	0	2.0	2.0	2.0	2.0
Sulfur (ppm)	339	339	61	338	685	322
E200 (vol. %)	41	36.7	47.1	47.1	47.1	59.4
E300 (vol. %)	83	81.1	83.6	83.6	83.6	89.7
Aromatics (vol. %)	32	29.0	25.7	25.7	25.7	26.4
Olefins (vol. %)	9.2	10.2	7.5	7.5	7.5	11.0

[1] The defined Clean Air Act Baseline Fuel
[2] The actual baseline fuel used in this study

effect in older vehicles.

Post-1981 model year vehicles were chosen because these vehicles were required to meet lower nitrogen oxide as well as hydrocarbon and carbon monoxide standards. As a result, NOx reduction catalysts were used for the first time. Since then, engine and catalyst technology has been steadily improving. Therefore, the response to fuel formulation on earlier models may not be necessarily the same as 1990 model year vehicles.

Two major changes with reformulated gasoline are the lower volatility and at least 2% oxygen content. Older technology vehicles have less precise fuel and air control and are expected to be more sensitive to fuel oxygen content. Because well maintained 1990 model year vehicles control fuel and air flow, oxygen content does not have much effect on emissions. Since the purpose of lower volatility is to reduce evaporative emissions, the effect on exhaust emissions is expected to be similar for older and current technology vehicles.

Experimental

Four test fuels and a baseline fuel were used in this program (See Table 1). The baseline fuel was blended to simulate the Clean Air Act Baseline fuel though some distillation and other parameters could not be exactly matched. Test fuels 1 through 3 were used to investigate the effect of sulfur on emissions. Fuel 4 was used to represent a low volatility gasoline though its distillation parameters were strikingly different.

Adding diethyl sulfide to fuel 1 produced the sulfur levels for fuels 2 and 3. Diethyl sulfide was chosen because its boiling point and molecular weight make it a mid-range gasoline component.

Ten vehicles were chosen to represent post-1981 technology (See Table 2). Four carburetted and six throttle-body fuel-injected (TBI) vehicles were used in this program. These represent the primary fuel delivery systems used in pre-1990 model year vehicles.

Since vehicles using reformulated gasolines would be subject to enhanced inspection and maintenance requirements, they were screened by the I&M-240 inspection test with the owner's fuel as received (EPA, 1992). Only vehicles that passed the IM-240 test were chosen for this program. The IM-240 test included pressure and purge checks for the integrity of the evaporative control systems as well as meeting the 0.8/2.0/20 gram per mile HC/NOx/CO cutpoints on the IM-240 driving cycle.

The testing order for the fuels was chosen randomly for each vehicle and is given in Appendix A along with vehicle specifications, and odometer readings. Random selection was used to reduce the carryover effect from one fuel to another in the average emissions effect. A baseline fuel was used at the beginning and end of each fuel set to measure any drift in the emission results.

For each fuel, the exhaust emissions were measured for a full FTP driving cycle. The raw emission results are given in Appendix A.

Because of lessons that were learned about vehicle instability during previous fuel testing, the following procedure was used to prepare vehicles prior to FTP testing. (Mayotte et al. (1994a) and (1994b), and Korotney (1995)) The tank was drained, then filled with the test fuel. The vehicle was driven on three consecutive LA-4 drving cycles during which emissions were determined. If the second and third LA-4 emission measurements were not within 10% of each other, the vehicle was driven until consecutive cycles produce consistent results. This procedure has produced more stable emission measurements.

Several fuels including the baseline fuel were tested twice, but all of the data was used. Repeat tests were treated by averaging the repeat with the initial test. No drift in the emissions using the baseline fuels was detected so all tested cars were included in the results.

Results

Sulfur Effect - The results for the ten car test fleet indicate that reducing sulfur will reduce both NMHC and NOx emissions. (See Table 3.) This is best observed by comparing the results of Fuel 3 and Fuel 1 where sulfur was increased from 61 to 685 ppm without changing any other parameters. The NMHC and NOx emission increase observed was statistically significant at greater than a 90% confidence level by pairing the observations of the two fuels. It is less clear that the emission results for Fuel 2 were significantly different than for Fuel 1. But the average effect was smaller because the sulfur increase was smaller.

Table 3 The Percent Emission Effect of Changing Only the Fuel Sulfur Level

Emission	Fuel 2 vs. Fuel 1	Fuel 3 vs. Fuel 1
NMHC	6.7 ± 5.5%[1]	8.9 ± 6.3%
Complex Model	5.2	12.0
NOx	3.6 ± 4.8	6.4 ± 4.9
Complex Model	10.0	14.7

1 90% Confidence Level for all uncertainties

The sulfur effect on NOx emissions was less and on NMHC emissions essentially the same as predicted by the complex model. The table shows that the NOx emissions increased less than half that predicted by the complex model with increasing sulfur.

Fuel Effects - For fuels 1, 2, and 3, the emissions effects compared to the baseline fuel in this study indicated substatially greater NMHC emission reduction for the older technology vehicles than predicted by the complex model for 1990 model year cars. (See Table 4.) Emission reductions may be due to changes in oxygen content, volatility reduction, or the distillation parameters, E200 and E300. The complex model predicts that lowering the volatility and raising E200 and E300 parameters reduces NMHC exhaust emissions for 1990 technology vehicles. However, fuel 4 did not produce significantly greater emission reductions than predicted by the complex model even though volatility was reduced and E200 and E300 were substantially raised. The emission results of fuel 4 suggests that oxygen content was primarily responsible for the greater NMHC exhaust emissions reductions for fuels 1, 2, and 3. A specifically designed study investigating the effect of these parameters would be necessary to confirm this supposition.

Based upon the results, the overall NOx emission results are similar to those predicted by the complex model. But as indicated above, less NOx reductions are expected with sulfur reduction.

Table 4 The Measured and Predicted Percent Emissions Effect for this Study's Fuels Compared to the Baseline Fuel

Fuel	NMHC	NOx
All 10 Vehicles		
1	-20.8 ± 3.2%[1]	-4.1 ± 6.9%
2	-15.9 ± 2.8%	-0.9 ± 7.5%
3	-14.1 ± 4.6%	2.0 ± 6.4%
4	-20.8 ± 4.4%	-1.9 ± 5.3%
EPA Complex Model (Phase 2)		
1	-14.1 %	-11.1 %
2	- 9.4 %	- 1.2 %
3	- 2.4 %	+ 4.2 %
4	-18.6 %	+ 0.5 %

1 90% confidence level for all uncertainties

The results shown in Table 5 indicate that the carburetted vehicles as compared to throttle-body injection vehicles may be more sensitive to gasoline reformulation and produce greater NMHC and less NOx reductions. The uncertainty limits are too large to draw a conclusion, but it points to an area for further study. Other work (AQIRP, 1990) has shown that carburetted vehicles may be more sensitive oxygen content, E200, or volatility changes. This study adds to the data currently available.

Table 5 The Percent Emissions Effect of the Test Fuels Compared to the Baseline Fuel on Carburetted and Throttle-Body Injection Vehicles

Fuel	NMHC	NOx
Carburetted Vehicles (n=4)		
1	-23.4 ± 5.2%[1]	+1.4 ±14.1%
2	-18.6 ± 5.8%	+7.0 ±20.0%
3	-16.9 ±13.7%	+7.2 ±17.8%
4	-26.3 ± 7.1%	-4.2 ±12.5%
Throttle-Body Injection (n=6)		
1	-19.2 ± 5.0%	-7.7 ± 9.1%
2	-14.1 ± 3.4%	-6.1 ± 3.0%
3	-12.2 ± 3.1%	-1.4 ± 4.7%
4	-17.1 ± 5.1%	-0.4 ± 6.8%

[1] 90% confidence level for all uncertainties

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Appendix A: Raw FTP Composite Data

VEHICLE	TEST #	DATE	FUEL	Mileage	HC (g/mi)	NOX (g/mi)	CO2 (g/mi)	CO (g/mi)	NMHC (g/mi)	MPG
1986	94-1504	02/22/90	Baseline	91,388	0.642	0.532	372	9.566	0.485	22.8
Mazda B2000	94-1505	02/23/90	Fuel 1	91,435	0.533	0.467	374	8.281	0.387	22.8
GTK2.0T2HFL8	94-1705	03/03/90	Fuel 1 Retest	91,714	0.498	0.516	368	7.217	0.364	23.3
Carburetted	94-1506	02/28/90	Fuel 2	91,595	0.512	0.543	374	7.127	0.379	22.9
	94-1507	02/27/90	Fuel 3	91,546	0.462	0.584	373	5.062	0.348	23.2
	94-1704	03/02/90	Fuel 3 Retest	91,674	0.496	0.539	368	7.020	0.368	23.3
	94-1508	02/24/90	Fuel 4	91,494	0.467	0.456	371	7.986	0.344	23.0
	94-1509	03/01/90	Baseline	91,634	0.592	0.598	374	7.888	0.454	22.8
1986	94-1510	02/22/90	Baseline	93,293	0.336	0.674	302	3.141	0.286	28.8
Chevrolet Nova	94-1511	02/28/90	Fuel 1	93,474	0.256	0.651	285	2.705	0.213	30.6
GNT1.6V2HFF1	94-1707	03/03/90	Fuel 1 Retest	93,586	0.249	0.670	276	2.764	0.208	31.5
Carburetted	94-1512	02/23/90	Fuel 2	93,342	0.290	0.636	286	2.932	0.244	30.4
	94-1513	02/24/90	Fuel 3	93,381	0.295	0.629	281	2.869	0.247	31.0
	94-1706	03/02/90	Fuel 3 Retest	93,544	0.291	0.677	283	2.994	0.243	30.7
	94-1514	02/27/90	Fuel 4	93,424	0.251	0.638	286	2.699	0.209	30.5
	94-1515	03/01/90	Baseline	93,503	0.327	0.639	285	3.502	0.279	30.4
1984	94-1683	03/09/90	Baseline	186,069	0.523	0.710	309	6.310	0.464	27.7
Honda Accord	94-1684	03/10/90	Fuel 1	186,109	0.419	0.710	311	4.870	0.368	27.7
EHN1.8V3FEF0	94-1687	03/15/90	Fuel 2	186,242	0.432	0.720	314	4.990	0.381	27.4
Carburetted	94-1685	03/13/90	Fuel 3	186,150	0.499	0.700	312	5.770	0.446	27.5
	94-1686	03/14/90	Fuel 4	186,195	0.415	0.700	306	5.250	0.370	28.1
	94-1688	03/16/90	Baseline	186,283	0.503	0.690	311	5.920	0.449	27.5
1983	94-1741	03/09/90	Baseline	110,054	0.452	0.510	321	4.120	0.408	27.0
Honda Accord	94-1743	03/13/90	Fuel 1	110,132	0.361	0.520	319	3.070	0.321	27.3
	94-1745	03/15/90	Fuel 2	110,232	0.375	0.590	317	2.520	0.337	27.5
Carburetted	94-1742	03/10/90	Fuel 3	110,093	0.361	0.580	318	2.270	0.322	27.5
	94-1744	03/14/90	Fuel 4	110,175	0.335	0.470	310	3.150	0.299	28.1
	94-1746	03/16/90	Baseline	110,271	0.562	0.440	310	5.990	0.514	27.6
	94-1877	03/22/90	Baseline Re	110,301	0.474	0.390	314	5.440	0.427	27.4
1985	94-2045	04/04/90	Baseline	64,040	0.507	1.610	354	3.850	0.462	24.5
Chevrolet Celebrity	94-2048	04/07/90	Fuel 1	64,158	0.439	1.390	349	3.600	0.394	24.9
FG2.5V5TPG7	94-2049	04/11/90	Fuel 2	64,197	0.445	1.490	351	3.490	0.400	24.8
TBI	94-2046	04/05/90	Fuel 3	64,079	0.476	1.540	355	3.690	0.430	24.5
	94-2047	04/06/90	Fuel 4	64,119	0.421	1.570	353	3.450	0.383	24.7
	94-2050	04/12/90	Baseline	64,252	0.534	1.650	350	4.130	0.488	24.8
1984	94-2053	04/04/90	Baseline	135,761	0.363	1.330	389	4.350	0.317	22.3
Pontiac 6000	94-2054	04/05/90	Fuel 1	135,801	0.294	1.120	382	3.480	0.252	22.8
EZG2.5V5TPG7	94-2055	04/06/90	Fuel 2	135,840	0.305	1.210	384	3.650	0.262	22.7
TBI	94-2056	04/07/90	Fuel 3	135,879	0.312	1.200	386	3.970	0.268	22.6
	94-2057	04/10/90	Fuel 4	135,974	0.320	1.180	373	4.740	0.279	23.2
	94-2058	04/11/90	Baseline	136,012	0.357	1.280	374	4.860	0.312	23.2
1986	94-2201	04/18/90	Baseline	62,432	0.299	0.870	366	3.588	0.246	23.8
Chevrolet Cavalier	94-2204	04/21/90	Fuel 1	62,548	0.226	0.717	367	2.843	0.180	23.8
G1G2.0V5XAG2	94-2205	04/24/90	Fuel 2	62,586	0.274	0.788	357	3.149	0.223	24.4
TBI	94-2202	04/19/90	Fuel 3	62,471	0.277	0.843	364	3.212	0.224	24.0
	94-2203	04/20/90	Fuel 4	62,509	0.235	0.819	368	3.149	0.190	23.7
	94-2206	04/25/90	Baseline	62,625	0.313	0.895	363	3.941	0.258	24.0
1985	94-2193	04/18/90	Baseline	119,346	0.734	1.010	436	6.940	0.653	19.7
Mercury Marquis	94-2196	04/21/90	Fuel 1	119,460	0.569	1.120	435	4.380	0.499	20.0
FFM3.8V5HHF8	94-2194	04/19/90	Fuel 2	119,384	0.637	1.040	435	5.170	0.564	19.9
TBI	94-2195	04/20/90	Fuel 3	119,422	0.604	1.110	430	4.930	0.536	20.2
	94-2197	04/24/90	Fuel 4	119,499	0.541	1.190	424	3.080	0.484	20.6
	94-2198	04/25/90	Baseline	119,537	0.660	1.160	426	5.510	0.591	20.3
1986	94-3129	06/15/90	Baseline	104,154	0.515	1.047	368	6.216	0.460	23.4
Ford Tempo	94-3130	06/16/90	Fuel 1	104,191	0.487	0.934	372	5.054	0.431	23.2
GFMM2.5V5HCF6	94-3131	06/19/90	Fuel 2	104,230	0.449	0.987	371	4.849	0.394	23.3
TBI	94-3133	06/21/90	Fuel 3	104,328	0.461	1.048	368	5.472	0.407	23.5
	94-3132	06/20/90	Fuel 4	104,269	0.471	1.055	367	4.546	0.424	23.6
	94-3134	06/22/90	Baseline	104,366	0.574	0.973	375	7.316	0.516	22.8
1985	94-3119	06/16/90	Baseline	115,460	1.065	2.480	430	9.300	0.998	19.8
Mercury Cougar	94-3123	06/22/90	Fuel 1	115,496	0.851	2.720	430	3.740	0.797	20.2
FFM3.8V5HHF8	94-3121	06/20/90	Fuel 2	115,553	0.921	2.480	423	7.150	0.857	20.3
TBI	94-3122	06/21/90	Fuel 3	115,589	0.954	2.660	422	6.340	0.897	20.4
	94-3120	06/19/90	Fuel 4	115,647	0.907	2.680	426	7.210	0.854	20.1
	94-3124	06/23/90	Baseline	115,684	1.008	2.670	427	8.480	0.945	20.0

Appendix B

IM-240 and FTP Correlations and Results

Inspection Results - For the 10 vehicles used in this study, it is informative to show that these vehicles are representative of in-use vehicles by comparing the IM-240 results with the FTP results. EPA modelling of exhaust emissions (Brzezinski, 1994) includes a correlation of FTP and IM-240 exhaust emissions for carburetted and throttle-body injection vehicles. The correlation is based upon a larger number of vehicles than in this study so there is a large uncertainty associated with any differences between this study and the EPA estimates. The EPA correlations that were used in this work are given in Appendix B.

The predicted HC emissions for the FTP based on the IM-240 results were quite close to those measured for the FTP in this study. (See Table B-1.) The predicted NOx emissions were lower for the TBI and higher for the carburetted vehicles. But generally the emissions measured in this study was comparable to the correlation used by EPA for emission factors estimates. This indicates that these were representative of the expected in-use vehicles when reformulated gasoline is used though no criteria have been established.

Table B-1 Emissions and Predicted Emissions from IM-240 Results

Test Cycle		HC (g/mi)	NOx (g/mi)
IM-240	TBI	0.34	1.18
	Carb.	0.28	0.81
Predicted FTP	TBI	0.53	1.05
	Carb.	0.48	0.72
Measured FTP	TBI	0.58	1.42
	Carb.	0.49	0.60

Of the vehicles screened for this study, 40% failed the test. Of the 25 vehicles screened for this study on the IM-240 test, 10 were carburetted and 15 were throttle-body injection vehicles. Four of the 10 carburetted failed the IM-240 test with 2 vehicles failing for NOx, one for CO, and one for both HC and CO emissions. Of the 15 throttle-body injection vehicles the 5 failed IM-240 test with 2 failing for NOx emissions, 1 for HC, 1 for CO, and 1 for both HC and CO.

<u>HC Correlation</u>
LOG (FTP-X) = ZML + DET*LOG(IM240)

	X	ZML	DET
TBI	0.180	0.00	0.9840
Carb.	0.195	0.00	0.9745

<u>NOx Correlation</u>
FTP = ZML + DET*IM240

	ZML	DET
TBI	0.0767	0.8234
Carb.	0.0000	0.8925

Table B-2 Emission Levels for the IM-240 and FTP Tests

Vehicle		IM-240	FTP
1	HC	0.23 g/mi	0.62 g/mi
	NOx	0.97 g/mi	0.57 g/mi
2		0.27	0.33
		0.97	0.66
3		0.23	0.51
		0.80	0.70
4		0.38	0.50
		0.50	0.45
5		0.30	0.52
		1.48	1.63
6		0.20	0.36
		1.13	1.31
7		0.32	0.36
		0.51	1.31
8		0.50	0.70
		1.21	1.09
9		0.22	0.54
		1.00	1.01
10		0.47	1.04
		1.75	2.58